ROLE OF DEUTERON NN*-COMPONENTS IN PROCESSES $\mathbf{pd \to dp}$ AND $\mathbf{pd \to dN^*}$

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Abstract

The contribution of nucleon isobar N^* exchanges to backward elastic pd-scattering is calculated on the basis of deuteron 6q-model and found to be negligible in comparison with the neutron exchange. It is shown that the pole amplitude of neutron pickup from the deuteron nN^*-component is favoured in the reaction $pd \to dN^*$ for backward going $N^*(1440)$ and $N^*(1710)$ at kinetic energy of incident proton of 1.5–2 GeV whereas the triangular diagram with subprocess $pp \to d\pi^+$ related to the usual $pn-$component of deuteron is considerable suppressed.

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1 Introduction

An idea of preexistence of nucleon isobars in the deuteron at short NN-distances suggested for the first time in Ref. [1] is compatible both with the meson exchange theory [2] and 6-quark picture of the deuteron structure [3]. Backward elastic pd-scattering, $pd \to dp$, is one source of information on the short-range structure of the deuteron. According to calculations [1] based on the Regge phenomenology and analysis [4] performed in the meson exchange theory the contribution of the NN^*-component to the $pd \to dp$ process is essential to explain the experimental data at energies $\sim 1GeV$. However, the application of the Regge-model at rather low energies as well as considerable uncertainties in knowledge on $meson - N - N^*$ vertices make these estimations questionable. Developed in last decade, the 6-quark model of the deuteron [5]-[8] provides a new regular approach to construction of dNN^*- vertices. In this model the deuteron structure at short relative NN-distances $r_{NN} \leq 1fm$ is determined by superposition of nonexcitated s^6 and excitated $s^4p^2 - s^52s$ 6-quark shell-model configurations. Presence of two-quantum excitations in the configuration $s^4p^2 - s^52s$ is a reason for the phenomenological repulsive core in the NN-interaction potential [7]. Besides, the excitated quark configuration leads to an admixture of a small NN^*-component in the deuteron wave function. The effective numbers and momentum distributions are calculated in the framework of this approach [8, 9]. Recently the results [9] for dNN^* vertices were found sufficient [10] to explain the available experimental data on the inclusive reaction of deuteron disintegration $d + A \to p(0^o) + X$[11] within the $n + N^*$-exchange mechanism.

In this work the contribution of N^*- exchanges to $pd \to dp$ (Fig.1,a) is calculated in the interval of incident proton kinetic energy in the labsystem of $T_p = 0.5 - 3GeV$ on the basis of the 6-quark model [8, 9] for dNN^*- vertices. As is found here, this contribution is negligible in comparison with the mechanism of neutron exchange calculated in the Born approximation (Fig.1, b) and with account of rescatterings (Fig.1,c-e). Furthermore we

investigate the reaction $pd \to dN^*$ for the backward going N^*-isobar in the framework of the neutron exchange (NE) pole diagram (Fig.1,f) and triangle diagram (Fig.1,g) of one-pion exchange (OPE). The experimental investigation of the $pd \to dN^*(1440)$ reaction is planned at SATURNE [12]. If the NE-mechanism dominates, this reaction can give the direct information on the deuteron nN^*-component. The OPE amplitude involves the usual np-component of the deuteron and masks the NN^*-component. However, as will be shown here, for the nucleon-like $N^*(1/2^+)$-states there is a kinematic region for the $pd \to dN^*$ reaction in which the OPE mechanism is considerably suppressed.

2 The model

The relativistic effects play an important role in the NE-mechanism at energies $\geq 1GeV$, especially for the $d \to p + N^*$ channel with large binding energy, $\varepsilon \sim 500MeV$ [13]. In order to allow for relativistic effects we use here the phenomenological relativistic approach for the three-body problem developed in Ref. [14]. In this the amplitude of the process $pd \to dB$, where B denotes either a proton (for $pd \to dp$) or N^* (for $pd \to dN^*$), in the framefork of one baryon exchange (OBE) can be written as direct generalization of the $pd \to dp$ formalism of Ref. [15]

$$A_{OBE} = 4\sqrt{E_d(E_p+E_N)E_{d'}(E_B+E_N)}\,\frac{\sqrt{s}-M_0}{E_N}\sum_{|N>}\left\{\Psi_{\lambda'}^{\sigma_p\sigma_N}(\mathbf{q}')\right\}^+\Psi_{\lambda}^{\sigma_B\sigma_N}(\mathbf{q}). \qquad (1)$$

Here $E_k = \sqrt{m_k^2+\mathbf{p}_k^2}$ and $\mathbf{p}_k$ are the energy and momentum of the k-th particle in the p+d c.m.s., m_k is its mass; $M_0 = E_N + E_p + E_B$; $\sqrt{s}$ is the invariant mass of the $p+d = d+B$ system; $\Psi_{\lambda'}^{\sigma_p\sigma_N}\,(\Psi_{\lambda}^{\sigma_B\sigma_N})$ is the deuteron wave function in the channel $d \to Np\,(d \to NB)$ normalized to the effective number, N_{pN}^d, of the corresponding channel

$$\frac{1}{2J_d+1}\sum_{\lambda,\sigma_p,\sigma_N}\int|\Psi_{\lambda}^{\sigma_p,\sigma_N}(\mathbf{q})|^2\,\rho_{pN}^{-1}(q)\,\frac{d^3q}{(2\pi)^3} = N_{pN}^d, \qquad (2)$$

where $\rho_{pN}(q) = 2\varepsilon_p(q)\varepsilon_N(q)/[\varepsilon_p(q)+\varepsilon_N(q)]$; $\varepsilon_k(\mathbf{q}) = \sqrt{m_k^2+\mathbf{q}_k^2}$; σ_j is the spin projection of the nucleon j (j=p,B,N); $\lambda\,(\lambda')$ denotes the spin projection of the initial (final) deuteron.

The sum over the internal states φ_N, including σ_N, of the transferred baryon N (neuteron or N^*) is assumed in Eq. (1). The combinator factor $(\sqrt{2})^2$ is included in Eq.(1) since the 6-quark deuteron wave function is fully antisymmetric. The arguments $\mathbf{q}$ and $\mathbf{q}'$ of the initial and final deuteron wave functions can be written in the following form

$$\mathbf{q}' = \mathbf{p}_p - \frac{\varepsilon_p(\mathbf{q}') + E_p}{\varepsilon_N(\mathbf{q}') + E_N + \varepsilon_p(\mathbf{q}') + E_p}\mathbf{d}', \tag{3}$$

$$\mathbf{q} = \mathbf{p}_B - \frac{\varepsilon_B(\mathbf{q}) + E_B}{\varepsilon_N(\mathbf{q}) + E_N + \varepsilon_B(\mathbf{q}) + E_B}\mathbf{d}, \tag{4}$$

the relations $\mathbf{p}_N = \mathbf{d} - \mathbf{p}_B = \mathbf{d}' - \mathbf{p}_p$ are used here which are valid in the p+d c.m.s. [14]; $\mathbf{d}\,(\mathbf{d}')$ is the momentum of the initial (final) deuteron. The amplitude (1) is related to the c.m.s. cross section of $pd \to dB$ as

$$\frac{d\sigma}{d\Omega} = \frac{1}{64\pi^2 s}\frac{p_B}{p_p}\overline{|A|^2}. \tag{5}$$

The basis for calculation of dNN^*-vertices is the fully antisymmetric 6q-wave function of deuteron which in the resonating group method (RGM) has a form

$$\Psi_d(1,\ldots,6) = \hat{A}\{\varphi_p(1,2,3)\varphi_n(4,5,6)\chi(\mathbf{r})\}. \tag{6}$$

Here φ_p and φ_n are the quark wave functions of proton and neuteron, $\chi(\mathbf{r})$ is the RGM distribution function for the pn component of deuteron and $\hat{A}$ is the quark antisymmetrizer. When deriving the function $\chi(\mathbf{r})$ one can either calculate it in the microscopic 6q-dynamics or construct it by means of RGM-renormalization procedure [8] for the conventional phenomenological wave function of deuteron in pn-channel, like Paris or RSC. The difference between the effective numbers for these two methods is negligible, of few percentage [8]. The translationally invariant shell model (TISM) state is used as the iternal state of quark motion in the baryon. The wave function $\Psi_\lambda^{\sigma_B\,\sigma_N}$ for the channel $d \to N + B$ entering Eq.(1) is determined by the overlap integral between the 6-quark wave function of the deuteron, Ψ_d, (6) and the product of the internal wave functions of

the baryons, φ_N and φ_B, as $\Psi_\lambda^{\sigma_B\,\sigma_N} = \sqrt{\frac{6!}{3!3!2}} < \varphi_N \varphi_B | \Psi_d >$. The details of the formalism and the effective numbers for N^* in the deuteron are presented in Refs. [8, 9].

Rescatterings in the initial and final states for the NE amplitude are taken into account here in the eikonal approximation on the basis of the method developed in Ref. [16]. As a result, besides the Born term (Fig.1, a or b), three additional terms arise allowing for pd-rescattering at small angles in the initial state (Fig.1,c), pp-rescattering in the final state (Fig.1, d) and rescatterings both in the initial and final states simultaneously (Fig.1,e).

The spin-averaged square of the NE-amplitude of the $pd \to dN^*$ reaction (Fig.1,f) takes the form

$$\overline{|A_{NE}(pd \to dN^*)|^2} = \frac{3}{64\pi^2} K^2 \rho_{pn}(q')\, \rho_{nB}(q)\, [u^2(q') + w^2(q')]\; \Phi^2_{N_B L_B}(q), \tag{7}$$

where K is the same kinematic factor as in front of the sum sign in Eq.(1), u and w are the S- and D-components of the deuteron function in the $d \to pn$ channel, $\Phi^2_{N_B L_B}(q)$ is the momentum distribution in the channel $d \to nN^*$ for the N^*-isobar with the number of internal excitation quanta N_B and internal orbital momentum L_B normalized by the condition $\int_o^\infty \Phi^2_{N_B L_B}(q) q^2\, dq = N^d_{nB}(2\pi)^3$. The corresponding formula for the NE mechanism in $pd \to dp$ follows from Eq.(7) after substitution $B \to p$, $\Phi^2_{N_B L_B}(q) \to u^2(q) + w^2(q)$. In the framework of the NE-mechanism the tensor polarization of the final deuteron in the $pd \to dN^*$ reaction has a form

$$T_{20}(\theta_{c.m.} = 180^o) = -\frac{1}{\sqrt{2}} \frac{w^2(q') - \sqrt{8} u(q')\, w(q')}{u^2(q') + w^2(q')}. \tag{8}$$

This formula coincides with the one for the $pd \to dp$ process within the NE-mechanism .

The triangular diagram OPE with the subprocess $pp \to d\pi^+$ was investigated in [17, 18] in the analysis of the $pd \to dp$ process. Generalization of the formalism from Refs. [17, 18] to the $pd \to dN^*$ reaction is quite obvious if we restrict ourselves to the nucleon-like states of N^*, $J^P = 1/2^+$. In this case the only difference between the

reactions $pd \to dN^*$ and $pd \to dp$ is the mass inequality, $m_p \neq m_{N^*}$. Consequently, the modification of the formalism from Refs. [17, 18] has a kinematic character. It results in the following form for the spin-averaged square of the OPE amplitude

$$\overline{|A(pd \to dN^*)|^2} = \frac{3}{2}\frac{\widetilde{G}^2}{4\pi}\,\widetilde{F}^2(k^2)\,\frac{E_{N^*}+m_{N^*}}{E_{N^*}^2}\,(f_{01}^2+f_{21}^2)\,\frac{3}{2}\overline{|A(pp \to d\pi^+)|^2}, \qquad (9)$$

where $\widetilde{F}^2(k^2)$ is the πNN^*-formfactor; for the estimation we use the monopole πNN-formfactor as $\widetilde{F}$; according to Ref.[19], for the Roper resonance $N^*(1440)$ the squared coupling constant $\widetilde{G}^2/4\pi$ in the πNN^*-vertex equals 14.7×0.472^2; the same value we use for the $\pi NN^*(1710)$ vertex in accordance with arguments of Ref. [4]; E_{N^*} and $\mathbf{p}_{N^*}$ are the total energy and momentum of the N^*-isobar in the labsystem; the nuclear formfactors for the S- and D- components of the deuteron (l=0, 2) $f_{l1}(p_{N^*})$ are expressed via r-space integrals of the product of the deuteron wave function $\psi_l(r)$ and the spherical Bessel function of the first order, $j_1(p_{N^*}m_{N^*}\,r/E_{N^*})$ (see details in Refs. [17, 18]). Such a form for $f_{l1}(p_{N^*})$ comes from the p-wave nature of the πNN and $\pi NN^*(1/2^+)$ vertices. Owing to the equality $j_1(x=0)=0$, the formfactor $f_{l1}(p_{N^*})$ becomes zero at the point $p_{N^*}=0$ and the OPE-amplitude (9) vanishes, too. The rest point in the labsystem for the N^*-isobar is at $T_p = 1.876 GeV$ for $N^*(1440)$, 2.75 GeV for $N^*(1535)$ and 6.86 GeV for $N^*(1710)$.

3 Numerical results and discussion

The numerical calculations are performed with the Paris wave function for the np-component and its RGM-modification [9] for the NN^*-component of the deuteron. The sum over ten TISM states listed in Tabl.2 of Ref.[9], for which the effective numbers $N^d_{NN^*}$ are not less than 10^{-5}, is carried out in the Eq. (1) in calculation of the OBE-amplitude of $pd \to dp$ process. The cross section of the $pd \to dN^*$ reaction is calculated here under assumption that N^* is a stable state to simplify the comparison with $pd \to dp$ process. The

contribution of N^*- exchanges to the $pd \to dp$ cross section is shown in Fig.2. The total contribution of N^*-states of positive parity (s-waves) and negative parity (p-waves) to the $pd \to dp$ cross section is by a factor of > 30 smaller than the neutron exchange. In the energy interval $T_p = 0.5 - 1GeV$ the p- contribution increases the OBE-cross section by a factor of ~ 1.3 due to interference with the neutron exchange amplitude. However, the interference between the s- and p-wave amplitudes of N^*-exchange is destructive. As a result, the total contribution of N^*-exchanges to the cross section and T_{20} of the $pd \to dp$ process is negligible. We should note that, on the contrary, in the inclusive reaction $d + A \to p(p^o) + X$ the interference between s- and p-waves of N^*-exchanges does not occure [9]. We found numerically that the cross section of $pd \to dp$ at $\theta_{c.m.} = 180^o$, $T_p = 1 - 3GeV$ within the NE-mechanism decreases by a factor $\sim 2 - 3$ due to rescatterings and practically does not change its form as a function of T_p (Fig.3,b). The tensor polarisation T_{20} is modified by the rescatterings by not more than 5-10%.

The small contribution of N^*-exchanges to $pd \to dp$ is mainly due to the small effective numbers of N^*-isobars in deuteron, $N^d_{NN^*} < 10^{-2}$. Unlike N^*-exchanges in the $pd \to dp$ amplitude including two dNN^* vertices (Fig.1,a), the NE-amplitude of the $pd \to dN^*$ reaction (Fig.1,f) contains only one dNN^* vertex. Therefore the modulus of this amplitude can be larger than that of the amplitude in Fig.1,a. Moreover, there is an additional enhancement factor for the NE-mechanism of the $pd \to dN^*$ reaction in the case of s-states of relative motion in the $d \to n + N^*$ channel, namely, the presence of a point with zero relative momentum $\mathbf{q} = 0$ (4) in this channel. For the Roper resonance the point $\mathbf{q} = 0$ lies at $T_p = 1.2GeV$ and for $N^*(1710)$ at 2.2 GeV. It is easy to find that the point $\mathbf{q} = 0$ arises in the nonrelativistic kinematics, too. For the N^* isobars of negative parity the NE-amplitude is strongly suppressed in the vicinity of the point $\mathbf{q} = 0$ because of p-wave behaviour of the momentum distribution in the dnN^* vertex. As follows from Fig.3,a, the modulus square of the NE-amplitude of the $pd \to dN^*(1710)$ reaction

is the same order of magnitude as that for the $pd \to dp$ process and by one order of magnitude larger than the OPE-contribution in the energy interval of $T_p = 1.5 - 2GeV$. For the Roper resonance $N^*(1440)$ the NE-contribution is also comparable with that for $pd \to dp$ (Fig.3,b). This conclusion is mainly determined by the effective numbers $2\,N^d_{NN(1710)} = 6.75\,10^{-3}$ [9], $2\,N^d_{NN(1440)} = 10^{-3}$ [8] and not changed after substituting the harmonic oscillator wave function $\varphi_{00}(q)$ with the oscillator parameter $b = 0.6fm$ [6] or $b = 0.8fm$ [9] for the RGM-modified Paris wave function [9]. Furthermore the NE-mechanism of the $pd \to dN^*$ reaction can be indentified by measurement of tensor polarisation. We found from Eq.(8) that the tensor polarisation of the final deuteron in the $pd \to dN^*$ reaction at $T_p = 1 - 3GeV$ is $T_{20} \sim 0.6 - 0.7$ both for the $N^*(1440)$ and $N^*(1710)$ nucleon isobar. T_{20} is approximately constant since at energies of $T_p = 1-3GeV$ the argument q' in Eq.(8) slowly varies in the interval of 0.7 - 0.8 GeV/c for $N^*(1440)$ and 0.9 - 1.0 GeV/c for $N^*(1710)$. Otherwise the tensor analyzing power of this reactions in respect of the initial deuteron is zero for the NE-mechanism, $t_{20} = 0$.

In accordance with the above notes after Eq. (9), the OPE mechanism predicts a deep minimum in the cross section of $pd \to dN^*(1440)$ at proton energy $T_p = 1.876GeV$ (Fig.3,b) which corresponds to the rest point of $N^*(1440)$ at that energy. Thus, in conclusion, there are favourable conditions in the interval $T_p = 1.5 - 2GeV$ to pick out the contribution of the NE-mechanism in the $pd \to dN^*$ reaction for backward going $N^*(1710)$ and $N^*(1440)$ nucleon isobars and to search for the corresponding NN^* components of the deuteron.

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Figure captions

Fig.1. The mechanisms of the $pd \to dp$ and $pd \to dN^*$ processes: the one baryon exchange (OBE) (a - f); the neutron exchange (NE) in the Born aproximation (b, f) and taking into account rescatterings (c - e); the triangular diagram of one-pion exchange (OPE) (g).

Fig.2. The calculated cross section of $pd \to dp$ at $\theta_{c.m.} = 180^o$ as a function of kinetic energy of incident proton in the labsystem T_p within the OBE mechanisms: the neutron exchange (full curve, NE), the positive parity N^* exchange (s), the negative parity N^* exchange (p), the total contribution of N^*-exchanges (s+p), the coherent sum of $n + N^*$ exchanges (s+p+NE).

Fig.3. The cross section of the $pd \to dN^*$ reaction at $\theta_{c.m.} = 180^o$ calculated within the different mechanisms as a function of T_p for $N^*(1710)$ (a) and $N^*(1440)$ (b): curve 1 - OPE, 2 - NE. The $pd \to dp$ cross section within the NE mechanism is shown by curve 3 (for the diagram in Fig 1,b) and 4 (for the coherent sum of four diagrams in Fig.1,b - e).

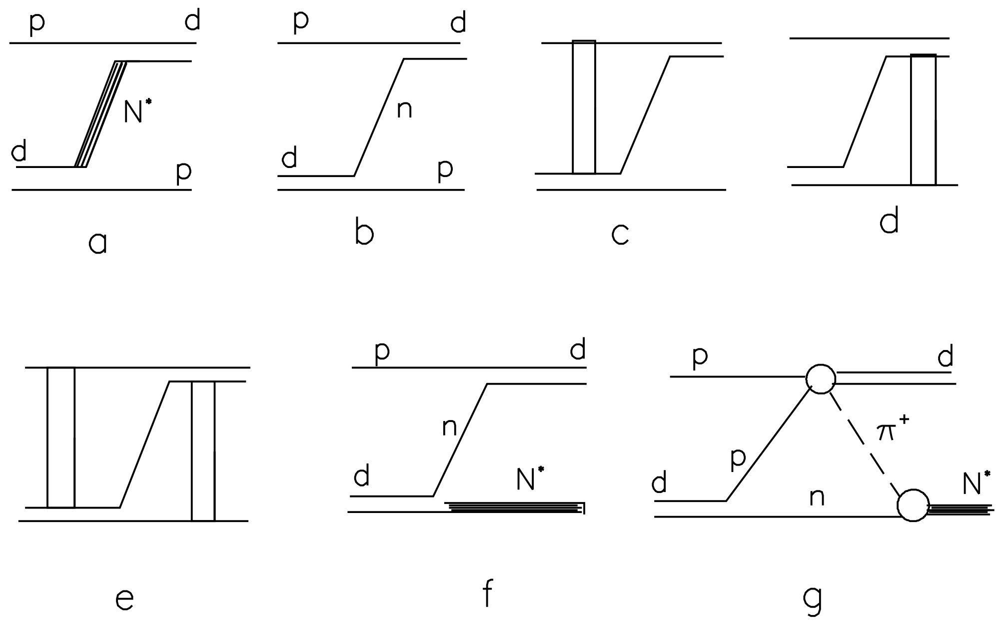
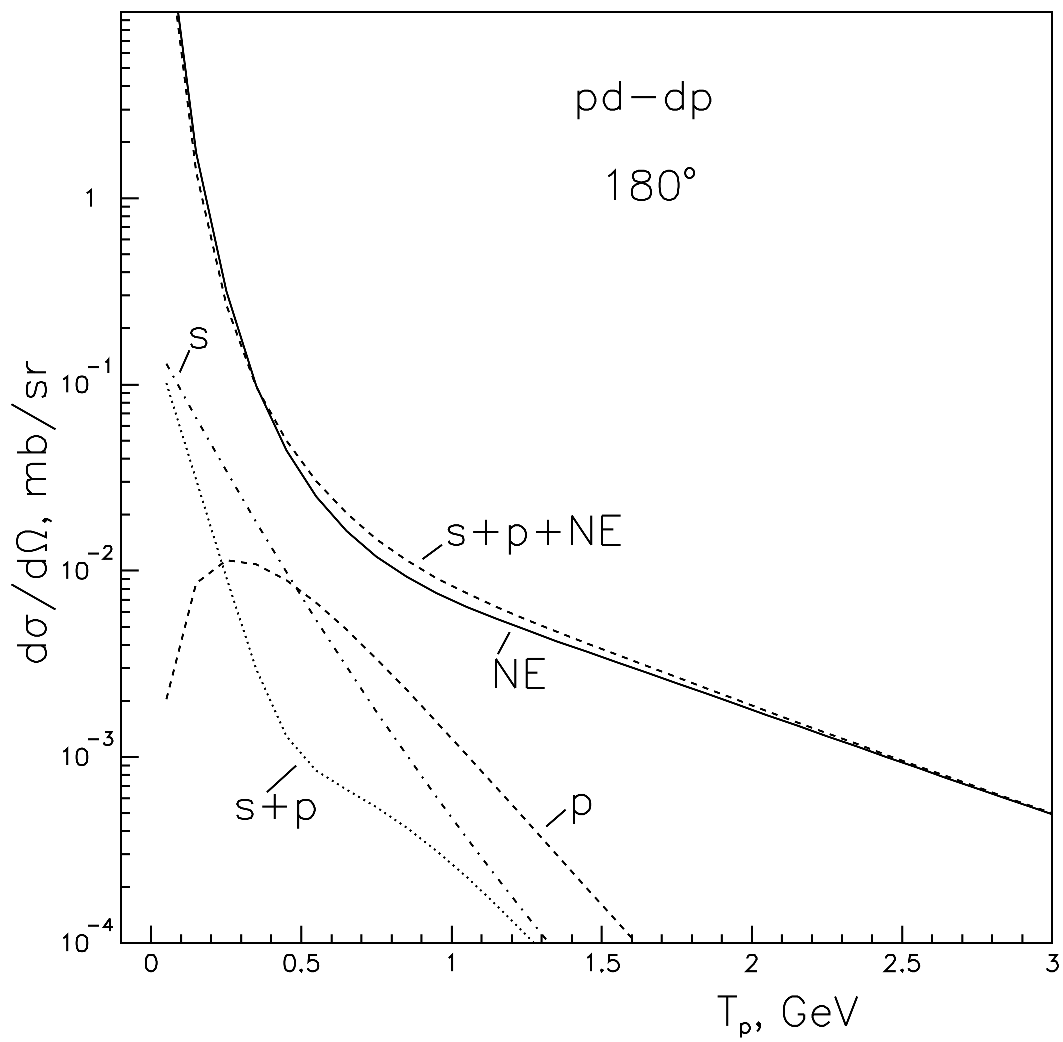


Figure 1:



pd−dp
180°
s
s+p+NE
NE
s+p
p
dσ/dΩ, mb/sr
1
10^−1
10^−2
10^−3
10^−4
0
0.5
1
1.5
2
2.5
3
T_p, GeV

Figure 2:

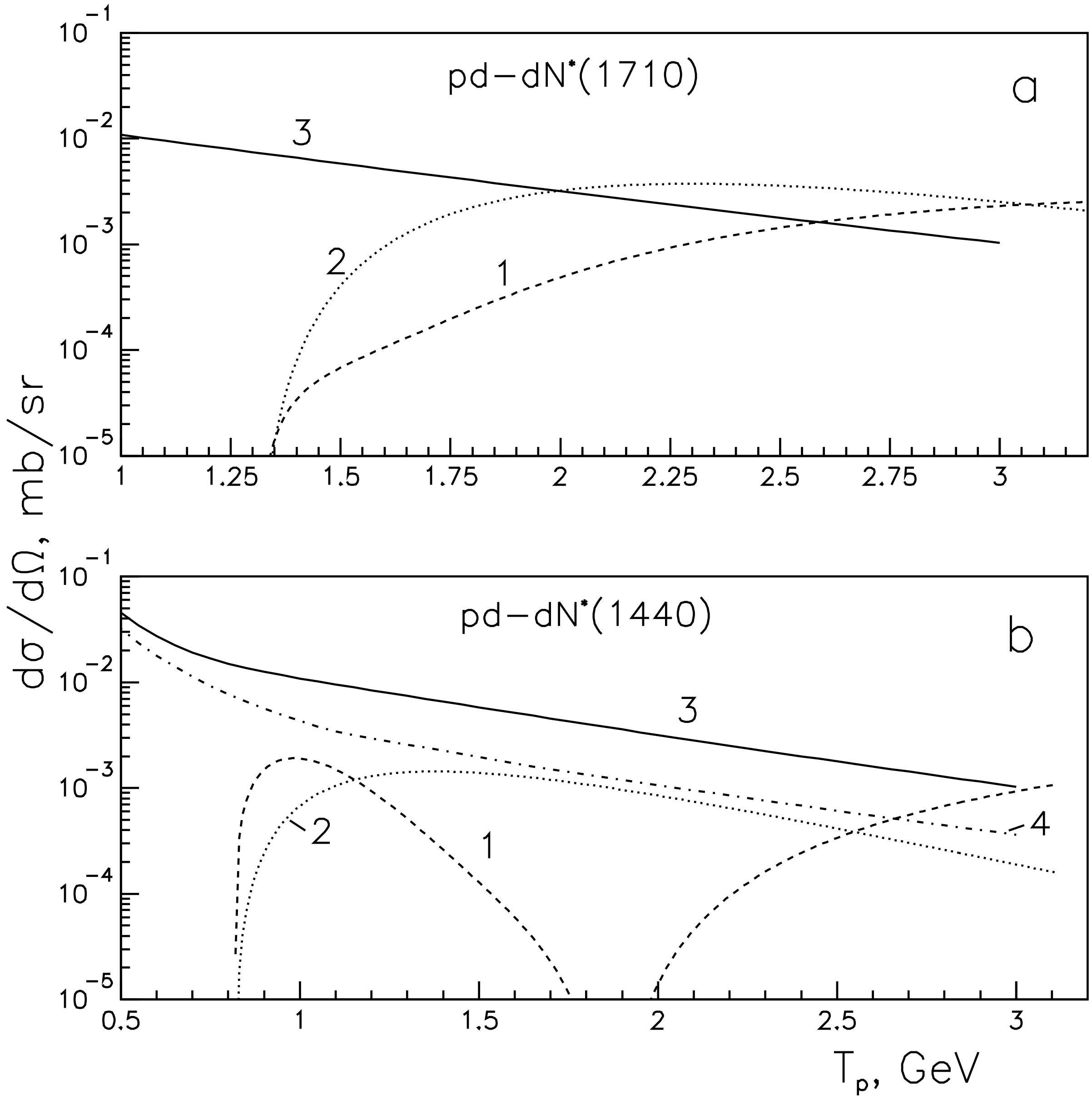


Figure 3: